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PATENT

## HIGH pH SLURRY FOR CHEMICAL MECHANICAL POLISHING OF COPPER

Inventors: Anne E. Miller  
A. Daniel Feller  
Kenneth C. Cadien

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### Background of the Invention

#### Field of the Invention

The present invention relates to the field of chemical mechanical polishing (CMP), and more specifically, to slurries and methods for chemical-mechanical polishing of metal.

#### Background

Advances in semiconductor manufacturing technology have led to the development of integrated circuits having multiple levels of interconnect. In such an integrated circuit, patterned conductive material on one interconnect level is electrically insulated from patterned conductive material on another interconnect level by films of material such as, for example, silicon dioxide. These conductive materials are typically a metal or metal alloy. Connections between the conductive material at the various interconnect levels are made by forming openings in the insulating layers and providing an electrically conductive structure such that the patterned conductive material from different interconnect levels are brought into electrical contact with each other. These electrically conductive structures are often referred to as contacts or vias.

Other advances in semiconductor manufacturing technology have lead to the integration of millions of transistors, each capable of switching at high

5 speed. A consequence of incorporating so many fast switching transistors  
into an integrated circuit is an increase in power consumption during  
operation. One technique for increasing speed while reducing power  
consumption is to replace the traditional aluminum and aluminum alloy  
interconnects found on integrated circuits with a metal such as copper, which  
10 offers lower electrical resistance. Those skilled in the electrical arts will  
appreciate that by reducing resistance, electrical signals may propagate more  
quickly through the interconnect pathways on an integrated circuit.  
Furthermore, because the resistance of copper is significantly less than that  
of aluminum, the cross-sectional area of a copper interconnect line, as  
15 compared to an aluminum interconnect line, may be made smaller without  
incurring increased signal propagation delays based on the resistance of the  
interconnect. Additionally, because the capacitance between two electrical  
nodes is a function of the overlap area between those nodes, using a smaller  
copper interconnect line results in a decrease in parasitic capacitance. In this  
20 way, replacing aluminum based interconnects with copper based  
interconnects provides, depending on the dimensions chosen, reduced  
resistance, reduced capacitance, or both.

As noted above, copper has electrical advantages, such as lower  
resistance per cross-sectional area, the ability to provide for reduced parasitic  
25 capacitance, and greater immunity to electromigration. For all these reasons,  
manufacturers of integrated circuits find it desirable to include copper in their  
products.

While advantageous electrically, copper is difficult to integrate into the  
process of making integrated circuits. As is known in this field, copper can  
30 adversely affect the performance of metal oxide semiconductor (MOS) field  
effect transistors (FETs) if the copper is allowed to migrate, or diffuse, into  
the transistor areas of an integrated circuit. Therefore copper diffusion

5 barriers must be used to isolate copper metal from those transistor areas. Additionally, unlike aluminum based metal interconnect systems which are formed by subtractive etch processes, copper interconnects are typically formed by damascene metal processes. Such processes are also sometimes referred to as inlaid metal processes. In a damascene process, 10 trenches are formed in a first layer, and a metal layer is formed over the first layer including the trenches. Excess metal is then polished off leaving individual interconnect lines in the trenches. The removal of the excess copper is typically accomplished by chemical mechanical polishing (CMP). Although there are many known variations of the damascene method of 15 metallization, the most common method for removing the excess copper metal is by CMP.

Accordingly, there is a need for CMP methods, materials, and apparatus to polish conductive materials such as copper.

## 20 **Summary of the Invention**

Briefly, a slurry for copper polishing has a pH between 7.5 and 12.

In a particular embodiment of the present invention, a slurry for polishing copper has a pH between 8 and 11.5, and includes a  $\text{SiO}_2$  abrasive, an  $(\text{NH}_4)_2\text{S}_2\text{O}_8$  oxidizer, a benzotriazole corrosion inhibitor, and a 25  $\text{K}_3\text{PO}_4/\text{K}_2\text{HPO}_4$  buffer.

## **Brief Description of the Drawings**

Fig. 1 is a schematic cross-sectional view of a copper damascene structure. This structure represents a post-plating, pre-polishing state of 30 fabrication.

5            Fig. 2 is a schematic cross-sectional view of the copper damascene structure of Fig. 1 after a conventional chemical mechanical polishing operation.

             Fig. 3 is a schematic cross-sectional view of the copper damascene structure of Fig. 1 after a chemical mechanical polishing operation in  
10            accordance with the present invention.

             Fig. 4 is a flowchart showing the operations in a process of polishing a thin film in accordance with the present invention.

             Fig. 5 is a Pourbaix diagram showing the domains of corrosion, immunity, and passivation of copper, at 25°C (after M. Pourbaix, Atlas of  
15            Electrochemical Equilibria in Aqueous Solutions, National Association of Corrosion Engineers, 1974, pg. 389).

### **Detailed Description**

             A method and slurry for the chemical-mechanical polishing of copper  
20            are described. In the following description numerous specific details are set forth to provide an understanding of the present invention. It will be apparent, however, to those skilled in the art and having the benefit of this disclosure, that the present invention may be practiced with apparatus and processes that vary from those specified here.

### **Terminology**

             The terms, chip, integrated circuit, monolithic device, semiconductor device or component, microelectronic device or component, and similar terms and expressions, are often used interchangeably in this field. The present invention is applicable to all the above as they are generally understood in  
30            the field.

5           The terms metal line, trace, wire, conductor, signal path and signaling medium are all related. The related terms listed above, are generally interchangeable, and appear in order from specific to general. In this field, metal lines are sometimes referred to as traces, wires, lines, interconnects or simply metal.

10           The terms contact and via, both refer to structures for electrical connection of conductors from different interconnect levels. These terms are sometimes used in the art to describe both an opening in an insulator in which the structure will be completed, and the completed structure itself. For purposes of this disclosure contact and via refer to the completed structure.

15           Design rules, as used herein, refers to a set of rules that define the width, spacing, and layer-to-layer relationships of the various elements that make up an integrated circuit. By way of example and not limitation, the minimum width of, and spacing between, interconnect lines on a particular interconnect level of an integrated circuit are specified in the design rules for  
20 any specific semiconductor manufacturing process.

Erosion, as used herein, refers to the amount of a layer, typically an interlayer dielectric, that is removed during the polishing of a metal damascene structure. Erosion is measured as a thickness, or distance, and more particularly, it is a measure of the distance between the original surface  
25 of the layer and its post-polish surface. Erosion is generally an undesirable result of overpolishing. The pre-polished thickness is shown as  $T_{ILD0}$  in Figure 1.

Examples of post-polish thickness can be seen in Figs. 2 and 3 and are identified as  $T_{ILD1}$  and  $T_{ILD2}$ . Erosion is defined as the total oxide loss  
30 represented by the differences,  $T_{ILD0} - T_{ILD1}$  and  $T_{ILD0} - T_{ILD2}$ . Typically, the erosion, or interlayer dielectric loss, is enhanced for structures such as serpentines, where the copper density is high relative to the dielectric density.

5           Recess, as used herein, refers to an amount of material, typically the metal of a metal damascene structure, that is removed during the polishing of the metal damascene structure. Recess is measured as a thickness, or distance, and more particularly, it is a measure of the distance between the post-polish surface of the interlayer dielectric and the post-polish surface of the metal. The recess is typically due to chemical attack rather than mechanical abrasion and is the main metal loss component of narrow, isolated metal lines. The spatial profile of a copper line due to recessing is typical flat. Examples of recess can be seen in Figs. 2 and 3 and are identified as  $T_{R1}$  and  $T_{R2}$ .

15           Dishing, as used herein, refers to an amount of material, typically the metal of a metal damascene structure, that is removed during the polishing of the metal damascene structure. Dishing is similar to recess in that it represents an overpolishing of the metal (i.e., excess material removal), however dishing typically results in a parabolic or concave shaped metal surface and is due to a mechanical interaction as the polish pad bends into the damascene structure. Dishing is measured as a thickness, or distance, and more particularly, it is a measure of the distance between the post-polish surface of the interlayer dielectric and the post-polish surface of the metal. Dishing typically occurs in metal structures that are wider than the minimum metal width permitted in a given set of design rules. Examples of dishing can be seen in Figs. 2 and 3 and are labelled as  $T_{D1}$  and  $T_{D2}$ .

          The expression, low dielectric constant material, refers to a material having a lower dielectric constant than silicon dioxide.

          Substrate, as used herein, refers to the physical object that is to be planarized by means of the CMP process. A substrate may also be referred to as a wafer. Wafers, may be made of semiconducting, non-semiconducting, or combinations of semiconducting and non-semiconducting

- 5 materials. Silicon wafers may have thin films of various materials formed upon them. These thin films may be planarized with CMP processing. Other substrate materials such as GaAs, silicon-on-sapphire, or silicon on insulator (SOI) may be planarized with CMP processing.

The term vertical, as used herein, means substantially perpendicular to  
10 the surface of a substrate.

RPM (also rpm) refers to revolutions per minute.

### Overview

- Polishing of copper metal layers in connection with the formation of  
conductive interconnect lines for integrated circuits is becoming more  
15 important for the semiconductor industry. Unlike aluminum metallization,  
which is typically formed on integrated circuits by subtractive metal etch,  
copper interconnect lines are typically formed by way of a damascene, or  
inlaid, metal process. Such a process requires the removal, typically by  
chemical mechanical polishing (CMP), of the excess copper. CMP has been  
20 used successfully for polishing interlayer dielectrics such as silicon dioxide.  
CMP has also been used to polish metals such as tungsten, particularly in the  
formation of contact plugs. However, copper is unlike either silicon dioxide or  
tungsten. Copper is a soft metal compared to tungsten which makes CMP  
more difficult to achieve. As predicated by thermodynamics, both copper and  
25 tungsten slurries can be tailored for operation in the passivating pH regime of  
the Pourbaix diagram. Figure 5 shows the Pourbaix diagram for copper. In  
support of this theory, the bulk dissolution rate or static etch rate of slurries  
approach zero at  $\text{pH} > 6$ . However, in practice, the copper film that forms  
may be reactive with ionic species such as  $\text{SO}_4^-$  or  $\text{Cl}^-$ , and thus, benefits  
30 from the addition of a corrosion inhibitor such as benzotriazole. Erosion,  
dishing, and recessing are difficulties encountered in the CMP of copper  
because of the chemical and physical properties of copper.



5 Conventional methods of copper polishing for integrated circuit manufacturing include using an alumina-based, or silica-based, slurry at a pH equal to or less than 7.5. CMP of copper with conventional copper polish slurries frequently results in high corrosion rates. Furthermore, when  
10 conventional copper polish slurries are modified to include a corrosion inhibitor, the result is a narrow process window in terms of concentrations, pressures, and pad conditions, all of which limit the robustness, and in turn the cost effectiveness, of the copper polish process.

Furthermore, use of many of the conventional slurries, having an abrasive concentrations in the range of approximately 4% to 5%, results in  
15 the occurrence of glazing during the polishing of a wafer. Glazing refers to a condition wherein grooves, or other non-planarities, in the surface of a polishing pad fill up with particles or other material common to conventional copper polishing processes. Glazing reduces the ability of the polish pad to accomplish the desired material removal function. This phenomenon is  
20 sometimes referred to as shut-down. This can result in a requirement for longer polish times, or interim conditioning on CMP tools which do not include in-situ pad conditioning.

A copper polish slurry, in accordance with the present invention, operates with a high pH of greater than approximately 7.5. In this range the  
25 slurry has a low static etch due to formation of a robust, protective layer. This slurry may additionally have  $S_2O_8^{2-}$  or  $Fe(CN)_6^{3-}$  as an oxidizer and can thus offer a high polish rate on the order of 7,000 to 10,000 angstroms per minute. This polishing rate does not decrease significantly during polishing. Such an inventive slurry offers a wide CMP process window such that the slurry and  
30 process parameters can be optimized to yield low recess, erosion, and dishing on patterned wafers.

5 Various embodiments of the present invention offer a number of advantages over previous methods and slurries. Embodiments of the present invention offer negligible static etch rates. With the addition of a corrosion inhibitor in this pH regime, a stable, robust, passivating layer is formed on the copper, thereby providing a wide CMP process window in terms of

10 concentrations, pad conditions, and polish pressures. Embodiments of the present invention provide an abrasive that substantially reduces or eliminates glazing, or shut down, during polish. Further embodiments of the present invention provide an abrasive that promotes high polish rates, and therefore high wafer throughput. Additionally, due to the substantial absence of

15 glazing, a strong, robust, mechanical endpoint signature at polish pressures below 3 pounds per square inch (psi) is obtained. Because the polish rates enabled by embodiments of the present invention are substantially insensitive to pressure reduction, and can be operated effectively at polish pressures below 3 psi, erosion and dishing are both reduced. Furthermore, erosion can

20 be tailored by reducing the  $\text{SiO}_2$  concentration to below approximately 5% without inducing a significant reduction in polish rate. In a further aspect of the present invention, a buffer system that improves uniformity and reduces defects is provided.

## 25 The Slurry

An exemplary slurry, in accordance with the present invention, for chemical mechanical polishing of copper, has a pH between 8 and 11, and includes a  $\text{SiO}_2$  abrasive, an  $(\text{NH}_4)_2\text{S}_2\text{O}_8$  oxidizer, a benzotriazole corrosion inhibitor, and a  $\text{K}_3\text{PO}_4/\text{K}_2\text{HPO}_4$  buffer.

30 An abrasive suitable for use in the embodiments of the present invention is a precipitated  $\text{SiO}_2$ . This precipitated  $\text{SiO}_2$  is preferred over a fumed, or gas phase,  $\text{SiO}_2$ . Precipitated  $\text{SiO}_2$  is sometimes referred to in this

- 5 industry as colloidal, although this term, i.e., colloidal, is not a technically accurate designation for this material.

In addition to  $(\text{NH}_4)_2\text{S}_2\text{O}_8$ , chemicals such as  $\text{K}_2\text{S}_2\text{O}_8$ , or  $\text{K}_3\text{Fe}(\text{CN})_6$  may be used as oxidizers.

- 10 Corrosion inhibitors which may be used as an alternative to benzotriazole include other forms of benzotriazole such as 5-methyl benzotriazole or 1-methyl benzotriazole.

- 15 In addition to the benzotriazole inhibitors, additional corrosion inhibitors containing  $\text{Ba}^{2+}$  or  $\text{Ca}^{2+}$  may be added to suppress the pitting corrosion that occurs in the presence of  $\text{S}_2\text{O}_8^{2-}$ . The addition of these cations getters  $\text{SO}_4^-$  species that otherwise attack the passive Cu-benzotriazole layer by forming an insoluble precipitate of either  $\text{BaSO}_4$  or  $\text{CaSO}_4$ .

Buffer systems which may be used as an alternative  $\text{K}_3\text{PO}_4/\text{K}_2\text{HPO}_4$  include  $\text{KH}_2\text{PO}_4/\text{KOH}$ ,  $\text{K}_2\text{HPO}_4/\text{KOH}$ , and  $\text{KHCO}_3/\text{K}_2\text{CO}_3$

- 20 In one embodiment of the present invention, a slurry includes 5 wt.% precipitated  $\text{SiO}_2$  as an abrasive, 0.05M  $(\text{NH}_4)_2\text{S}_2\text{O}_8$  as an oxidizer, 0.005M benzotriazole as a corrosion inhibitor, and 0.175g/l  $\text{K}_3\text{PO}_4$  and 0.046g/l  $\text{K}_2\text{HPO}_4$  as a buffer system. Alternative embodiments may include  $\text{SiO}_2$  in the range of 2 to 10 wt. %.

- 25 Those skilled in the art and having the benefit of this disclosure will further recognize that it is not necessary to use a corrosion inhibitor, such as benzotriazole as part of the inventive slurry. Rather, this example is provided simply to illustrate the present invention. Those skilled in the art will further appreciate that a slurry formulated in accordance with the present invention will also include some reaction products of the various ingredients.

30

## 5 Method

In an embodiment of the present invention, a copper damascene structure is polished to form individual interconnects. Fig. 1 shows a copper damascene structure. An interlayer dielectric layer (ILD) is patterned to form ILD **102** on a surface of a wafer as illustrated in the figure. ILD **102** has a thickness represented by  $T_{ILD0}$  in Fig. 1. A copper diffusion barrier **104** is formed over the exposed surfaces of the wafer and ILD **102**. Various materials may be used as the copper diffusion barrier. Tantalum and tantalum nitride are often proposed as advantageous copper diffusion barriers. Typically a copper seed layer is then formed on copper diffusion barrier **104**. A complete copper layer **106** is then formed, typically by plating, over diffusion barrier **104**.

Fig. 2 illustrates the results of conventional copper CMP. More particularly, erosion, recess, and dishing are all illustrated in the figure. The post-polish thickness of ILD **102** is shown as  $T_{ILD1}$ . The difference between  $T_{ILD0}$  and  $T_{ILD1}$  is called erosion. The erosion, (i.e.,  $T_{ILD0} - T_{ILD1}$ ) is typically measured in the center of a dense array such as a serpentine and is typically much greater than the erosion measured in a large open field. Recess, represented by  $T_{R1}$ , affects the thickness of the post-polish copper **106**, and is measured from the top surface of the post-polish ILD **102** to the top surface of post-polish copper **106** as shown. Wide metal lines are particularly susceptible to a phenomenon known as dishing. Dishing, represented by  $T_{D1}$ , shows the additional material removed from wide metal lines.

Fig. 3 illustrates the results of copper CMP in accordance with embodiments of the present invention. Erosion, recess, and dishing are all illustrated in Fig. 3, but it can be seen that these exist to a lesser extent here than in Fig. 2. The post-polish thickness of ILD **102** in Fig. 3 is shown as  $T_{ILD2}$ . In Fig. 3 recess is represented by  $T_{R2}$ , and dishing is represented by  $T_{D2}$ . It can be seen that copper CMP in accordance with the present

- 5 invention produces a smaller erosion  $T_{ILD2}$ , recess  $T_{R2}$ , and dishing  $T_{D2}$ . This results in achieving the desired cross-sectional areas for copper interconnect. Table 1, below, shows the results obtained when polishing with a high pH slurry compared to a conventional slurry.

Table 1

Slurry	Conventional Slurry	High pH Slurry	High pH Slurry
pH	7.1	8.5	8.5
Pressure (psi)	3.75	3.75	2
Erosion (nm): 90% Copper Density	573	334	193
Dishing (nm): 100 $\mu$ m line	221	87	45
Recess (nm): 1 $\mu$ m line	41	3	0.5

10

An embodiment of the method of polishing a thin film on a wafer, in accordance with the present invention, is described in conjunction with Fig. 4.

- As is well known, in a typical CMP system, a wafer is placed face down on a rotating table covered with a polishing pad, which has been coated with a slurry. A carrier, which may be attached to a rotatable shaft, is used to apply a downward force against the backside of the wafer. A retaining ring may be used to center the wafer onto the carrier and to prevent the wafer from slipping laterally. By applying the downward force, and rotating the wafer, while simultaneously rotating a slurry covered pad, a desired amount of material may be removed from the upper surface of a thin film on the surface of the wafer.

20

5            Fig.4 shows a flow diagram of a process embodying the present invention. At block **402**, a high pH slurry is prepared, delivered to, and dispensed onto, a polishing pad. The high pH slurry, as described above, is typically in the range of 7.5 to 12, and may be in the range of 8 to 11. Then, as shown at block **404**, a wafer with a copper damascene structure formed  
10 thereon, is brought into contact with the polishing pad. As shown at block **406** the copper damascene structure is polished. Typical polishing conditions using an orbital polisher are a down force of approximately 3.75 psi, an orbital speed of approximately 310 rpm, a wafer rotational speed of approximately 10 rpm, a slurry flow rate of 200 ccm, and delta P of -0.1 psi. Delta P is the  
15 pressure difference exerted on the top and bottom of the wafer and allows fine control of the rate at the edge of the wafer. Stacked polishing pads such as the IC1000, with a Suba-4 sub-pad, both made by Rodel, Inc. of Newark, Delaware, can be used with the high pH slurry to polish copper films. FX-9 pads from Freudenberg of Lowell, Massachusetts, can be also used.  
20 Removal rates of approximately 8505 angstroms per minute have been obtained with within wafer non-uniformity (1 sigma) of 6.5%.

Copper diffusion barriers, such as, for example, tantalum or tantalum nitride, are also successfully polished with slurries and polishing conditions in accordance with the present invention.

25            Methods and slurries in accordance with the present invention may be used with various interlayer dielectric materials. For example, even though SiO<sub>2</sub> has traditionally been the dielectric material used between interconnect levels on integrated circuits, various low-k dielectric materials, including but not limited to, SiOF may also be used with embodiments of the present  
30 invention.

The motor current endpoint signal obtained with embodiments of the present invention are stronger than those found with conventional copper

- 5 CMP processes. This improved mechanical endpoint correlates with the absence of glazing.

### Conclusion

Embodiments of the present invention provide high pH slurries for chemical mechanical polishing of copper films.

- 10 An advantage of some embodiments of the present invention is that the polish time can be reduced thus reducing manufacturing cost.

A further advantage of some embodiments of the present invention is that dishing is reduced.

- 15 A still further advantage of some embodiments of the present invention is that erosion is reduced.

A still further advantage of some embodiments of the present invention is that the polish end point signal is improved as compared to that obtained in conventional methods.

- 20 It will be apparent to those skilled in the art that a number of variations or modifications may be made to the illustrative embodiments described above. For example, various combinations, slurry pH, slurry delivery rate, pad rotation speed, pad temperature, and so on, may be used within the scope of the present invention.

- 25 Other modifications from the specifically described apparatus, slurry, and process will be apparent to those skilled in the art and having the benefit of this disclosure. Accordingly, it is intended that all such modifications and alterations be considered as within the spirit and scope of the invention as defined by the subjoined Claims.